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Diffractive Production of Neutral Vector Mesons at THERA

James A. Crittenden [1]
Physikalisches Institut, University of Bonn, Nußallee 12
53115 Bonn, Germany

We consider the contribution to our understanding of vacuum-exchange processes to be made by investigations at the proposed electron-proton collider THERA. Recent results have highlighted the value of such studies for testing quantum chromodynamical descriptions of both long-range and short-range strong interactions. Stringent quantitative constraints have been provided by exploiting the opportunity to correlate scaling behaviour with helicity selection in exclusive and semi-exclusive vector-meson production. After reviewing the progress achieved by the measurement programs presently being carried out by the H1 and ZEUS collaborations at HERA, we discuss the performance criteria imposed by such investigations on the THERA accelerator complex and on the detector design. We conclude that the study of vector-meson production will form an essential component of the THERA physics program beginning with the early turn-on stage of the machine and continuing throughout the achievement of its full high-luminosity potential.

1 Introduction

Investigations of vector-meson production at THERA will confront our understanding of strong interaction dynamics, meson and baryon partonic structure, confinement mechanisms, flavour symmetries, scaling laws and helicity selection rules with detailed and multi-various extensions of the wealth of information obtained from the HERA programs presently being carried out by the H1 and ZEUS collaborations. Along with an unprecedented ability for detailed investigations of elastic and total photon-proton cross sections in the Regge limit of high energy, the electron-proton collider experimental strategy has established the research field of short-distance vacuum-exchange processes, or "hard diffraction", as a subject of essential importance to studies of Quantum Chromodynamics. While many of these research topics have built on a foundation of knowledge derived from decades of measurements, many others are completely new and only beginning to receive theoretical attention. All the topics have stimulated widespread theoretical and phenomenological interest, confirming existing theoretical prejudices in some cases, and clearly guiding theoretical approaches in others. The experimental opportunity presented by the THERA accelerator design directly addresses the need for an extension of the energy range both for approaches based on Regge phenomenology and for those based on perturbative and nonperturbative QCD. Even more importantly, THERA will extend the kinematic reach in momentum transfer by more than an order of magnitude, providing clean and detailed test of quantitative perturbative calculations of strong vacuum-exchange processes.

There are several simple reasons for the extraordinary variety of theoretical physics concepts addressed by the study of diffractive vector-meson production in electron-proton interactions. Even at a fixed electron-proton centre-of-mass energy, a broad range of energies in the photon-proton centre-of-mass system is available for investigation. Such a broad range of energy is of essential importance for studies of the weak energy dependence of soft diffractive processes. The corresponding access to the low-x region means that the coherence length of the virtual photons in the proton rest frame is much longer than the diameter of the proton [1], resulting in an unambiguous definition of virtual-photon/proton cross sections and hence the opportunity to study their scaling behaviour and helicity-transfer characteristics. Figure 1 shows the energy dependence of this cross section measured at HERA.

The remarkably steep energy dependence at high photon virtuality reflects the steep rise in the F_2 structure function at low x. Such high energies and wide rapidity ranges provide access to the kinematic region of diffractive processes, where the momentum transfers are much smaller than the kinematic limit. In the context of Regge phenomenology, recent investigations interpret the Q^2 dependence exhibited in the photon-proton cross section as evidence for the discovery of a second, "hard" Pomeron [3]. HERA results also show that accurate measurements can be made at momentum transfers far exceeding the hadronic confinement scale yet also fulfilling this diffractive condition. The analysis of exclusive and semi-exclusive vector-meson production (see Fig. 2) in the photon-dissociation region ensures the selection of vacuum-exchange processes [4]. Since this selection can be done with little

[1]Present address: Deutsches Elektronen-Synchrotron, Notkestr. 85, 22603 Hamburg, Germany

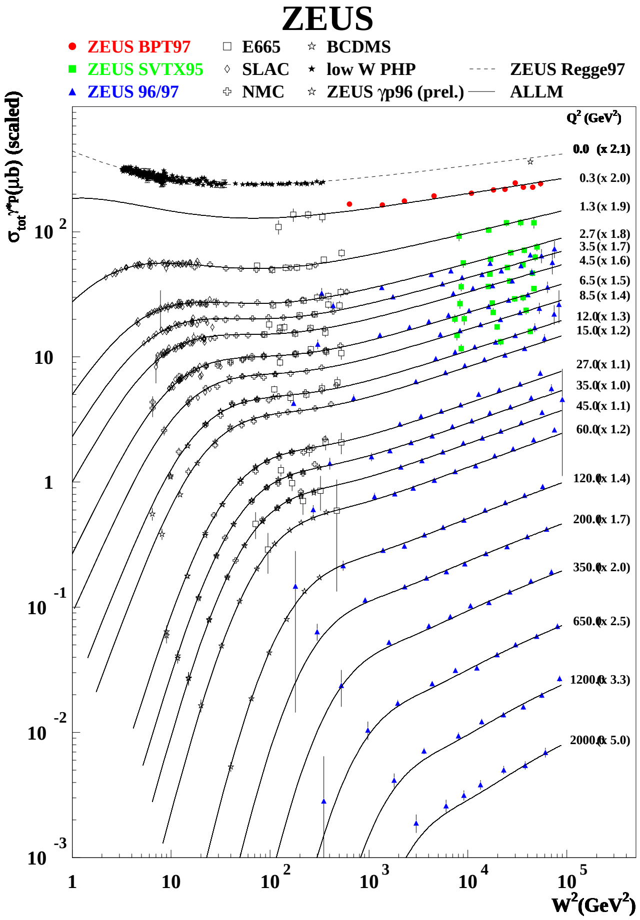


Figure 1: *The photon–proton cross section* $\sigma_{tot}^{\gamma^* p}$ *as a function of the squared centre–of–mass energy for various values of* Q^2*. The curves represent calculations using the ALLM parton distribution function parameterisations [2]*

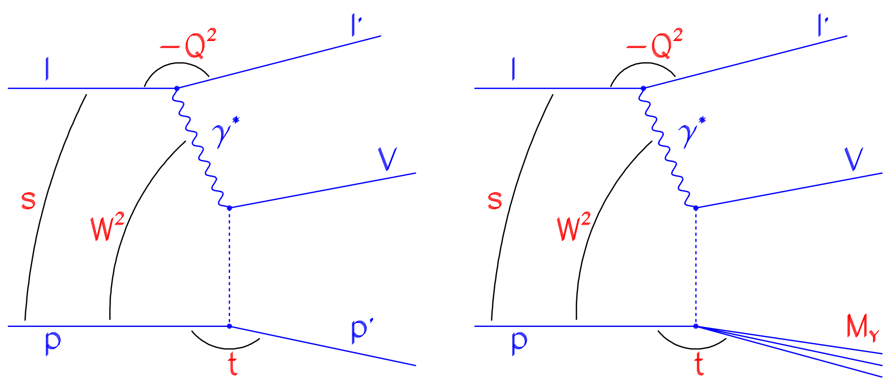


Figure 2: *Schematic diagrams of a) exclusive and b) semi-exclusive electroproduction of vector mesons. Such processes permit the study of vacuum-exchange processes in perturbative and non-perturbative kinematic domains, including the correlation of the helicity-transfer structure with the observed power-law scaling with momentum transfer for momentum transfers exceeding the hadronic confinement scale. The proton-dissociative process can be studied in both the nucleon-resonance and high-mass regions, providing information on Regge factorisation and on proton structure*

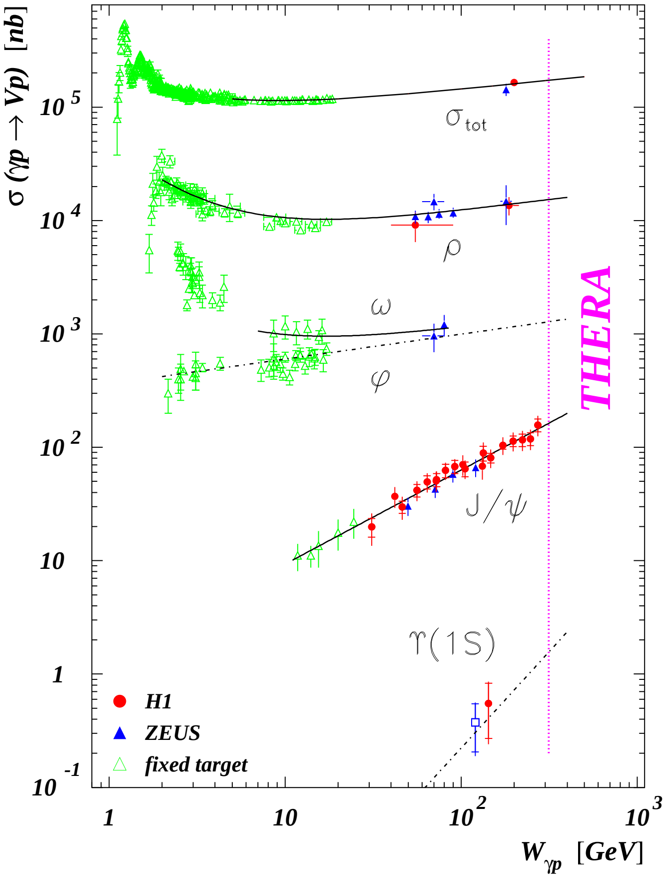


Figure 3: *Energy dependence of vector-meson photoproduction cross sections for ρ^0, ω, ϕ, J/ψ, and Υ mesons [14]*

influence on the kinematics of the reaction, general questions concerning its characteristics can be addressed, in particular the momentum-transfer scaling behaviour. At low momentum transfer, this permits investigation of phenomena described by Regge theory, such as the Pomeron trajectory and unitarity [5]. At high momentum transfer, such experimental studies address the strong interaction dynamics of vacuum exchange on distance scales much smaller than the confinement scale, presently a subject of active theoretical speculation. Particular to these studies of the production of phase-space-isolated vector mesons is the clean experimental environment allowing exploitation of the two-charged-particle decays to measure spin-density matrices with high accuracy. Quantitative assessment of helicity-violating amplitudes provides information on the partonic structure of the vector meson [6]. Since the momentum-transfer scaling behaviour is correlated to the helicity structure of the interaction [7, 8], these measurements provide strict constraints on field theoretical approaches and the associated power-law scaling features. The proton-dissociative process can be studied in both the nucleon-resonance and high-mass regions, providing information on Regge factorisation and on proton structure.

This highly varied phenomenology provides an extraordinarily rich experimental laboratory for testing new theoretical ideas. We will see in the following that the proposed THERA project is particularly well adapted for tests of quantum chromodynamical descriptions of this high-energy domain.

2 Lessons from HERA

Experimental investigations of vector-meson production at HERA [9–12] (see [13] for a review) have provided a wide variety of insights into the dynamics of both soft and hard diffractive processes. The high flux of quasi-real photons from the electron beam permitted detailed measurements of both elastic and proton-dissociative photoproduction of ρ^0, ω, ϕ, J/ψ, and Υ mesons. Power-law scaling with the photon-proton centre-of-mass energy, $W_{\gamma p}$, was observed for the J/ψ, as is illustrated by Fig. 3.

It is instructive to compare the energy dependence of these vector-meson production cross sections to the photon-proton cross sections shown in Fig. 1, where the steep energy dependence arises from the x dependence of the gluon density in the proton. The steep energy dependence measured for J/ψ mesons encouraged a number of theoretical approaches based on perturbative QCD [15]. Figure 4 shows a diagram illustrating this approach. Salient features of such calculations are an energy dependence determined by the gluon density in

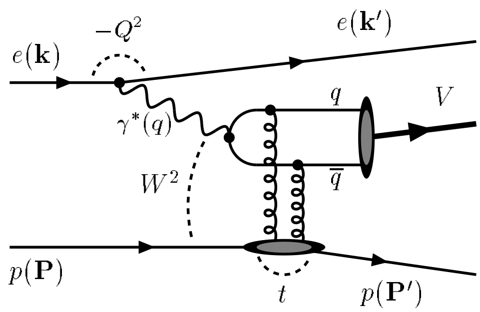


Figure 4: *Schematic diagram illustrating exclusive vector-meson production as mediated by the exchange of a gluon pair in a colour-singlet state*

the proton, flavour symmetry and the predominance of the longitudinal cross section for the light vector mesons at high momentum transfer. The HERA measurement of Υ photoproduction resulted in theoretical investigations [16] which predict a very strong energy dependence into the THERA region, with a large contribution from the off-diagonal gluon density. The phenomenological success of these calculations supports the view that the factorisation scale can be related to quark mass. Factorisation theorems have also been the object of theoretical investigations invoking the photon virtuality [8, 17, 18] and the momentum transferred to the proton [19] as hard scales in the production of vector mesons. These calculations demonstrated remarkable sensitivity to the gluon density in the proton, since the forward cross sections were shown to be proportional to its square. Measurements at HERA of ρ^0, ω, ϕ electroproduction and high-t photoproduction have served as testing grounds for these calculations. Of particular interest is the experimental access to the helicity structure of these processes via analysis of decay-angle distributions, since these reflect not only the helicity selection rules but also meson structure [6]. Figure 5 compares the ZEUS

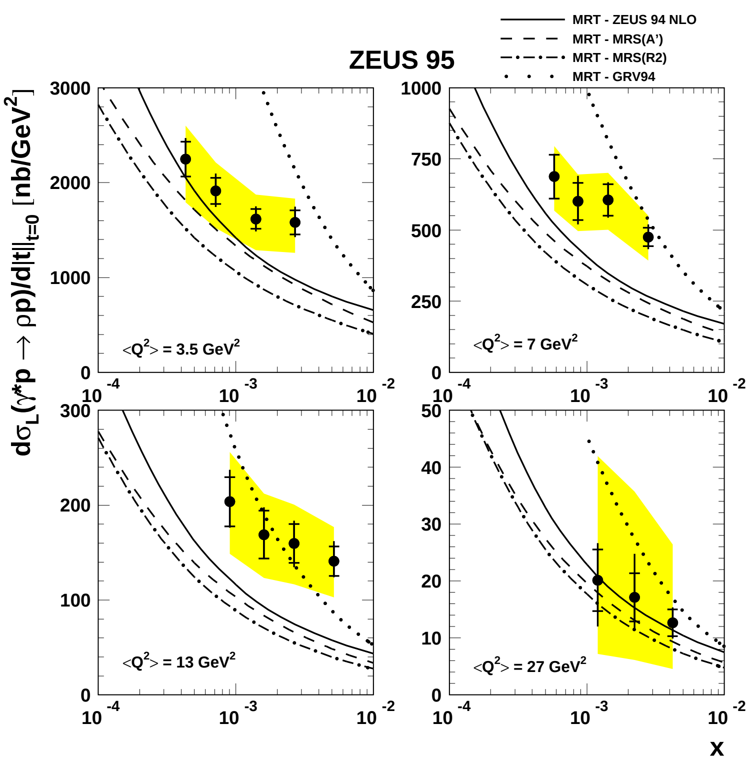


Figure 5: *The measured forward longitudinal cross section,* $\mathrm{d}\sigma_{\mathrm{L}}^{\gamma^{*}\mathrm{p}}/\mathrm{d}|t|\Big|_{t=0}$*, as a function of* x *for* ρ^0 *electroproduction [10]. The inner error bars represent statistical uncertainties; the outer error bars indicate the quadratic sum of statistical and systematic uncertainties. The shaded areas indicate additional normalisation uncertainties due to the proton dissociation background subtraction as well as the measured values of the* $R = \sigma_{\mathrm{L}}^{\gamma^{*}\mathrm{p}}/\sigma_{\mathrm{T}}^{\gamma^{*}\mathrm{p}}$ *ratio and the* t*-slope parameter* b*. The curves show the predictions by Martin, Ryskin and Teubner [18] and correspond to various gluon parameterisations, indicated as follows: full lines – ZEUS 94 NLO [20], dashed lines – MRSA′ [21], dashed-dotted lines – MRSR2 [22], and dotted lines – GRV94 [23]*

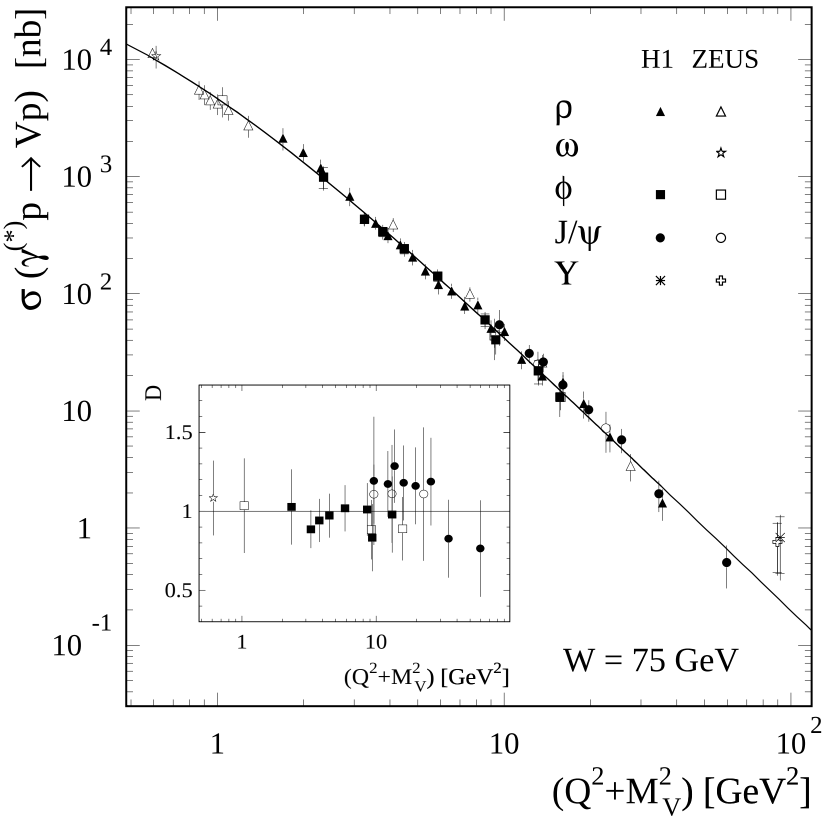
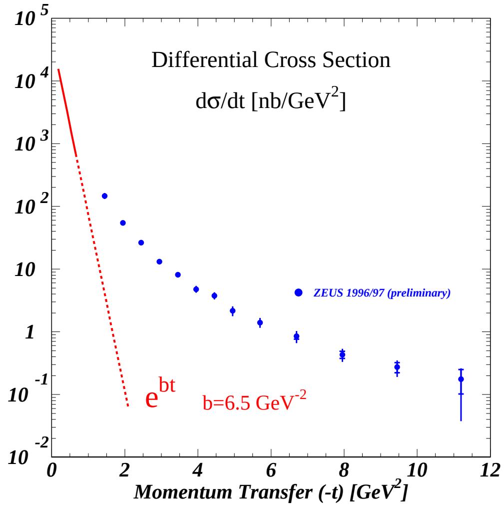


Figure 6: *H1 and ZEUS measurements of the cross sections $\sigma(\gamma^* \to Vp)$ as a function of ($Q^2 + \mathrm{M}_\mathrm{V}^2$) for elastic ρ^0, ω, ϕ, J/ψ and Υ production at the fixed value $W = 75\,\mathrm{GeV}$. The cross sections were scaled by SU(5) factors according to the quark charge content of the vector mesons. The error bars show statistical and systematic uncertainties added in quadrature. The curve corresponds to a fit to the H1 and ZEUS ρ^0 data, and the ratio, D, of the scaled ω, ϕ and J/ψ cross sections to this parameterisation is presented in the insert*

measurement of the differential cross section $\mathrm{d}\sigma_\mathrm{L}^{\gamma^\star \mathrm{p}}/\mathrm{d}|t|\Big|_{t=0}$ for ρ^0 production to the results of QCD calculations [10], illustrating the degree of consistency. The H1 collaboration has shown a remarkably consistent scaling behaviour common to the ρ^0, ω, ϕ, and J/ψ mesons by plotting the production cross sections as a function of $\mathrm{Q}^2 + \mathrm{M}_\mathrm{V}^2$, as shown in Fig. 6 [9]. This smooth behaviour is surprising from the point of view of the QCD models, given that the helicity analyses have shown the relative contributions of the longitudinal and transverse cross sections to depend strongly on Q^2, and the QCD models predict very different scaling behaviour for these two contributions. An investigation into high-t ρ^0 and ϕ photoproduction by the ZEUS collaboration [24] has recently turned up another surprise. This first measurement of vector-meson photoproduction at momentum transfers far exceeding the hadronic confinement scale, extending into a region where power-law scaling is observed, permits an accurate determination of the power. It was found that the ϕ/ρ^0 ratio reaches the SU(3) symmetric value in the same region of momentum transfer where the power-law scaling takes over from the exponential dependence observed at low t. The measurements of the decay-angle distributions showed the vector mesons to be transverse. This result, together with the extremely hard spectrum observed in the t distribution (see Fig. 7) [25], appears to be at odds with the QCD helicity selection rules [19].

These studies of exclusive vector-meson production have shown that the transition region from the domain of applicability of perturbation theory to the domain where long-distance strong-interaction dynamics applies can be scanned in photon virtuality and in the momentum transfer at the proton vertex. Such measurements have led to detailed theoretical consideration of the interaction size scaling with energy [26,27] and the relationship of diffraction to the mechanism of confinement [28].



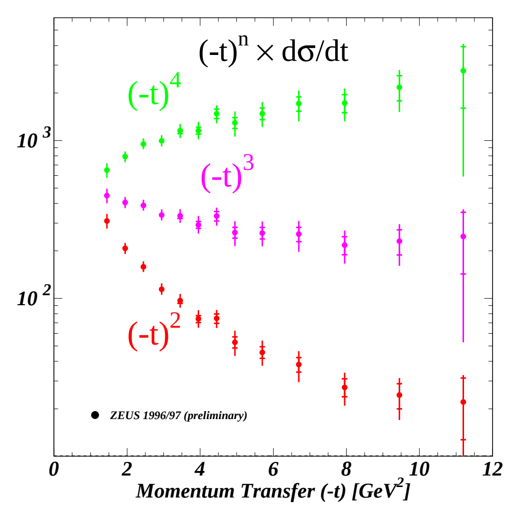


Figure 7: *a) Differential cross section* $\frac{d\sigma}{dt}$ *for the process* $\gamma + p \rightarrow \rho^0 + Y$*, where* Y *is a dissociated proton state. The line shows the* t *dependence measured for this process* $\gamma + p \rightarrow \rho^0 + Y$ *(*$\propto e^{6.5\cdot t}$*) [11] at low* $|t|$ *(solid line) and its extrapolation to higher* $|t|$ *(dashed line) for comparison. b) Differential cross section* $\frac{d\sigma}{dt}$ *multiplied by (-t)*^{n}*, where n=2, 3, 4*

3 Requirements on the performance of machine and detector

Measurements of vector-meson production at THERA will benefit not only from the extended kinematic reach to low x (high energy, wider rapidity range) and high Q^2, but also from the improved coverage of the THERA detector at small angles and from tagging systems in both the proton and electron flight directions designed with forethought and the benefit of the experience obtained at HERA. This experience has made clear the importance of careful design and close interaction with the THERA machine group. In the forward direction, the lack of high-t acceptance in the proton spectrometers prevents HERA studies of essential importance to QCD descriptions of exclusive processes. A lack of instrumentation in the the region of proton dissociation has resulted in the dominant source of systematic uncertainties for the measurement of elastic cross sections being the subtraction of this background. At THERA, improvement will come from requirements on the detector geometry independent of those imposed by studies vector-meson production [29], but further instrumentation of the low-M_Y region must also be taken into careful consideration. In the rear direction, a series of photoproduction taggers with associated bending magnets to select off-beam-momentum electrons will provide full coverage of the available range in W. The additional tracking coverage in the rear direction required by the investigations of inclusive processes at low-x will enable precise measurements of the vector-meson decay products, and so permit accurate reconstruction of t and and the decay-angles at high W. This is particularly important for the light vector mesons, since the hadronic decays used for their identification, together with the limited rear tracking in the H1 and ZEUS detectors result in a limitation to the W range of $W \lesssim 150$ GeV.

The program of measurements described above has been performed with an integrated luminosity corresponding to that estimated for less than one year's running time at THERA. The weak energy dependence of the diffractive cross sections at low momentum transfer for the light vector mesons ensures a high data rate during the early THERA running, making vector-meson production a principal contribution to the early physics program, just as was the case at HERA. However, many of the HERA studies of vector-meson production will remain statistics-limited. In particular, multiply differential studies of the perturbative region of photon virtuality and momentum transfer to the proton require high integrated luminosity. Another example of investigations requiring stable accelerator performance at high luminosity are those of diffractive J/ψ and Υ photoproduction. Elastic electroproduction of Υ mesons, where effects of the off-diagonal parton densities are dominant, await THERA operation. The helicity analyses of vector-meson production benefit from the longitudinal electron polarisation of the electron beam at THERA, since the spin-density matrix elements arising from circular photon polarisation are otherwise inaccessible [30]. The high cross sections at low momentum transfer and the need for high statistics in the kinematic region of

applicability of perturbative calculational techniques mean that the study of vector-meson production will play an important rôle in the THERA physics program beginning with the early turn-on stage of the machine and continuing throughout the achievement of its full high-luminosity potential.

4 Conclusions

The proposed THERA accelerator complex is conceived in the interest of extending the energy frontier in our understanding of electron-proton interactions. Simple extrapolation from the experience gained during the first nine years of HERA operation yield the reliable conclusion that THERA will make essential contributions to our understanding of the dynamics of strong interactions and, in particular, to the application of Quantum Chromodynamics as a means to achieve this understanding. The theoretical descriptions of the short-distance vacuum-exchange processes under investigation at HERA remain in their infancy; the discovery potential remains high. The parameters of the THERA machine directly address limitations to the present investigations of vector-meson production at HERA. The broad kinematic ranges in energy and momentum transfer accessible to the experimental investigation of diffractive vector-meson production ensure that such studies will make essential contributions to the THERA physics program throughout the entire duration of its operation.

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